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Provisional Manuscript

WIND-TUNNEL TESTS OF THE GROUND EFFECT ON AIRCRAFT MODELS */1

Alexandre de Sievers

Discussion of ground effect during takeoff and landing of aircraft with short wingspans. The matter is considered to be important and difficult to predict. The method of representing the ground by a fixed flat plate is used in the experiment discussed here. Although a deficiency of the method is the development of a limiting boundary layer on the plate representing the ground, it is considered that the approximation obtained is adequate when applied to wings of delta form. Comparative tests by the plane method and the mirror-image method apply to wings of different degrees of sweepback as well as to a model with a tail plane.

1. Resumé

The interaction of the ground during the takeoff and landing phases of aircraft of low aspect ratio is very important and difficult to define by calculation.

Therefore, experimental methods must be used: The simplest means of representing the ground in a wind tunnel is to study the mockup in the presence of a fixed "floor".

Despite the imperfection of this method, due to the development of a boundary layer on the "floor" or plate representing the ground, the obtained approxi-

* Numbers in the margin indicate pagination in the original foreign text.

mation is sufficient for cases in which the experiments refer to aircraft models with sweptback wings in delta planform.

Comparative tests with the "floor method" and with the mirror-image method, whose results are reported here, refer to wings of differing sweepback angles as well as to an aircraft mockup with rear tail unit.

2. Introduction /2

For a large number of years, aerodynamics have more or less disregarded wind-tunnel experiments on the influence of the ground effect.

The reasons for this are numerous. One factor is the imperfection or the unsuitability of the experimental means used in wind tunnels and another factor is the availability of methods for predicting such ground effects.

Among the latter, we should specifically mention the method of rheoelectric analogy, which is highly valuable for wings without sweepback, as well as a number of calculation methods which mostly are based on the general theory of biplanes.

These computational methods are an economical procedure for obtaining sufficiently approximate results, so long as the application is limited to aircraft with relatively large wing aspect ratio and without distinct sweepback, i.e., wings that might be covered by the Prandtl theory of wings of finite span, to which such calculations generally refer. However, in this case the ground effect is difficult to calculate if the wings show considerable hyperlift, corresponding to takeoff and landing conditions.

With the development of slender wings with low aspect ratio and of aircraft with short takeoff or vertical takeoff (S/V.T.O.L.) and, finally, of ground-effect platforms, it has become indispensable to resume experimental laboratory studies on the ground effect.

Four principal methods were developed in the various Research Centers:

Artificial floor, fixed in the wind-tunnel test section, with the model being weighed in the presence of this "floor" at variable altitudes.

Mirror image of the mockup, arranged symmetrically to the model weighed relative to a plane simulating the ground.

Moving carpet or conveyor belt whose rate of displacement is equal to that of the velocity of flow in the wind tunnel; here, the model is weighed at variable altitudes above this ground "without parasite boundary layer".

Carriage running on rails and carrying the aircraft model which latter is towed relative to a fixed "ground", at variable altitudes.

This brief discussion is concerned mainly with a critical evaluation of the results obtained by the first of these methods, in the wind tunnel at Cannes.

The investigations concerned exclusively aircraft models or aircraft /3
characterized by a low aspect ratio, since it has been known for long that the floor-type method leads to erroneous results when applied to wings of large aspect ratio.

To criticize the data obtained with a fixed floor, the results were repeated by the mirror-image method which, if certain precautions are taken, permits a correct simulation of the ground effect.

To emphasize the importance of this problem, it is useful to indicate the order of magnitude of the ground effect on the lift (Fig.1), for thin wings of different planform and aspect ratio. The ground effect also shows in an increase in aerodynamic fineness ratio and by a rearward shift of the aerodynamic center.

3. Description and Criticism of Experimental Methods /4

3.1 Wind-Tunnel Mounting

3.1.1 Mirror-Image Method

This method, in agreement with the classical artifice used for an analytical interpretation of the data for the ground effect problem, consists in identifying the interaction of the ground effect with the influence exerted on the mockup by an "image" symmetrically arranged with respect to a fictive ground.

The practical arrangement, used in the Cannes wind tunnel, is shown in Fig.2: weighed model, suspended on the balance in a tilted position along the diameter of the jet, with the image model suspended from a network of threads. The struts of the wind-tunnel balance intersect the image model without making contact. The angle-of-attack controls of the two models are conjugated.

3.1.2 Floor Method

The weighed model is mounted on the balance under the conditions described above but in the presence of a plate serving as floor (Fig.3). The altitude adjustment is obtained by vertical translation of the floor.

Development of this particular suspension required a certain number of preliminary studies:

> Determination of a suitable form for the leading edge of the floor and an initial orientation of this latter with respect to the axis of the wind tunnel, so as to obtain a uniform velocity field in a sufficiently large domain.

Correct definition of the reference velocity (wind-tunnel jet divided into two channels by the floor).

Correction of the walls used for this particular configuration of the jet.

3.2 Similitude Restrictions between Flight and Wind Tunnel, and Drawbacks Inherent to the Mounting

3.2.1 Relative Motion

No observations were made on kinematic similitude.

In fact, with the mirror-image method, the fictive ground constitutes a surface of two-dimensional flow. However, it is obvious that the velocity there is not uniform and also not equal to the velocity at infinity upstream of V_0, as would be required by a rigorous observation of the conditions of relative motion. It follows from this that the image method does not make allowance for the effect of ground friction. However, this particular point is usually considered as being of no practical consequence.

The lack of kinematic similitude has a much more serious influence on the /5
data obtained by the "floor" method.

In fact, a correct realization of the relative motion would mean that the floor, relative to the aircraft model, is moved at the same velocity V_0 as that of the nonperturbed flow (for example, method of the conveyor belt).

The stationarity of the floor results in the generation of a considerable boundary layer whose presence leads to a distortion of the potential flow.

3.2.2 Limitation of the Extent of the Ground and Influence of the Tunnel Walls

The limitation of the "ground" on the dimensions of the wind-tunnel jet and the presence of the wind-tunnel walls impose conditions on the flow whose limits differ from those corresponding to actual flight. However, it is possible to take this into consideration by making corresponding corrections to the test results which, under ordinary experimental conditions, are relatively minor. All subsequent results will carry the same corrections.

Let us mention that the plane of symmetry of the weighed models and of the mirror image (see Section 3.1.1) is not strictly a symmetry plane of the tunnel jet. However, calculation shows that the error introduced by this in the calculus of correction is of an order of magnitude considerably lower than that of the sensitivity threshold of the measurements.

3.2.3 Inaccuracies Resulting from the Model Suspension

Although the suspensions for the aircraft models are quite discrete and the weighed mockup is suspended by its pressure side* the following statements must be made:

In the floor method, the support struts that traverse this floor may create a local interference with the boundary layer of the floor. Visualizations show that flow separations may actually occur, but only at greatly negative angles of attack of the aircraft model.

In addition, the influence of the peripheral play in the openings for passage of the struts has been systematically investigated. A floor of maximum width, which latter must not be exceeded, has thus been defined.

In the mirror-image method, the image of the mockup is traversed by the suspension of the weighed mockup, without contact.

* In this manner, the interaction between support and model is much more reduced if the model is suspended by the suction side (flow separation at the root of the supports).

However, practical experiments have shown that the lift of the mirror image of the model is only slightly modified by the holes for passage of the struts. A fortiori, the influence of these openings on the interaction between mirror image and weighed aircraft model is no doubt negligible.

In addition, various tests made during the wind-tunnel experiments have shown the excellent symmetry of the flow obtained with an image model and, specifically, the absence of any definite interaction of the wakes. /6

3.2.4 Test Reynolds Number

The pre-existing turbulence of the wind tunnel and the low value of the Re makes measurements of the ground effect unreliable in the vicinity of maximum lift.

Fortunately, the angles of wing-tip stall in the case of low aspect ratio, which were the main point investigated here, are higher than those usually obtained in the immediate vicinity of the ground.

3.3 Comparative Results Obtained with Wings of Low Aspect Ratio

Here, the measurements were made on a rectangular wing of aspect ratio 2, having a thick plano-convex profile $e/\ell \simeq 22\%$; other tests were made on a series of flat wings of delta form, with various sweepbacks.

All these wings had the same surface and were centered at 55% of the mean chord.

3.3.1 Rectangular Wing $\lambda = 2$

The results of these tests are very distinct, indicating that the floor method furnishes excessive errors in this case.

Let us first investigate the behavior of the boundary layer of the floor.

An excellent visualization obtained at the ONERA by H.Werle in the hydrodynamic tunnel (Fig.4) shows the characteristic differences in the flow spectra observed with image models and with the floor system.

The rapid thickening of the boundary layer of the floor, noted upstream of the wing, is due to the adverse pressure gradient induced by the wing. Thus, as soon as the altitude becomes sufficiently low, even a separation of flow slightly upstream of the wing takes place (Fig.4 corresponds to this stage).

However, this burble point is absorbed again in the laminar flow created in the convergent zone formed by the wing and the floor. Beyond the leading edge, a second separation of flow takes place.

It is thus obvious that the limiting conditions relative to a plane ground, which are to be imposed on the potential flow due to the floor, are replaced by poorly defined conditions of a nonplanar edge of the boundary layer.

Conversely, the flow spectrum, obtained by the mirror-image method, satisfies the desired conditions.

In the wind tunnel, overall visualizations show that the same difficulties of flow are encountered on the floor as they are observed in a hydrodynamic /7 tunnel.

The few results shown in Fig.5 make it possible to define the consequences of these parasite phenomena:

Whereas it was expected that the ground effect would be overestimated by the floor method because of the reduction in effective altitude due to the presence of the boundary layer, exactly the opposite takes place.

This result, which appears quite paradoxical, is due to the curvature imposed on the flow by the boundary layer which osculates the floor. In particular, below the wing, the front of this boundary layer cuts out a sort of fluid wedge (see Fig.4) whose influence, in first approximation, manifests itself in a reduction of the angle of attack of the wing.

This statement is confirmed by the photographs in Fig.4 which, specifically, indicate that the stagnation point on the rounded leading edge is located much closer to the suction side of the wing in the presence of a floor than in the presence of an imaged wing.

3.3.2 Delta Wings of Various Sweepback

In the wind tunnel, the investigation of the wall flow along the floor does not show flow separations such as were observed in a rectangular wing.

Because of the pressure distribution induced on the ground, a negative transverse gradient of the symmetry plane toward the marginal extremities takes place, which favors an evacuation of the boundary layer by lateral drainage. This favorable effect is shown by the spectrum of the wall flow of the floor, made visible by schlieren, in the presence of delta wings.

Visualizations obtained in the hydrodynamic tunnel with a delta wing of 70° sweepback confirmed that the boundary layer of the floor is much less affected than in the presence of a straight wing. This highly favorable circumstance manifests itself in a definite improvement of the mode of representation of the ground by a floor, as shown in Fig.6 with respect to a delta wing of 75° sweepback (flat wing with cambered leading and trailing edges).

However, the distortions - although much more attenuated than those observed in rectangular wings - still persist. Their direction and their relative extent are a function of the altitude and of the angle of sweepback (Fig.7).

Specifically, the increase in lift due to the ground effect is either overestimated or underestimated, depending on whether the predominant influence of the boundary layer on the potential flow corresponds to a reduction in effective altitude or else to a curvature which, among other parasite effects, produces a reduction in the effective angle of attack.

The reduction in sweepback of the wing, other conditions being equal, tends to emphasize the parasite effect corresponding to the curvature of flow. An increase in angle of attack acts in the same direction. /8

Conversely, an inverse tendency is observed on increasing the rated altitude of the aircraft model.

A relatively vague confirmation of the satisfactory overall representation of the ground effect by the use of a floor, in the case of a sweptback wing at reasonable relative heights, is given by comparative tests made by the RAE, on an aircraft model of a configuration close to that of delta wings of $\varphi = 70^{\circ}$, performed in the Cannes wind tunnel (Fig.8).

The experiments by the RAE were made on a moving belt as well as on a fixed floor (stationary conveyor belt).

The differences between these data are of the same nature and of the same order of magnitude as those in the Cannes wind tunnel with the mirror-image wing and with the floor method.

4. Ground Effect on Simplified Aircraft Models /9

Two configurations were investigated:

tailless aircraft with delta-gothic wing of 60° sweepback;

aircraft with rear tail plane, equipped with a wing of 55° sweepback.

In both cases, rather roughly designed mockups were used, containing thin flat wings with acute dihedral leading and trailing edges; elevons or cambered flaps mounted to the wing by interchangeable hinges, etc.

The overall geometry of the second mockup, which is shown in Figs.1 and 2, necessitates a brief remark.

Independently of the possible interest of this configuration, the low position of the tail unit is completely justified for tests that are meant to control the validity of the method of representing the ground by a floor, since the tail unit would be at very low altitudes during the actual test and thus, to the absolute maximum, would be subject to the influence of possible flow perturbations that might occur along the floor.

4.1 Tailless Aircraft Model

Although an aircraft (Fig.9) is involved here which has a wing of nominal (60°) sweepback, the shape of the wing tips and the presence of a fuselage nose result in the fact that, in its overall geometry, this model is characterized by a mean sweepback greater than 60°. Consequently, the nature of the parasite interaction of the boundary layer of the floor with the corresponding distortions of the experimental results are related to those observed in a pure delta wing with 75° sweepback (dominance of the effect of an altitude reduction with respect to that produced by the flow curvature).

The curves in Figs.9 and 10 show, as a function of the altitude, the development of some aerodynamic characteristics of the model, determined by the mirror-image method and by the floor method:

The lift increment ΔC_L due to the ground effect is slightly overestimated in the data obtained with the floor method. Conversely, these same data minimize the increase in fineness ratio and, compared to tests with the image aircraft model, show a slight increment in nose heaviness ΔCm, at low angles of attack.

These systematic errors, affecting the results, are partially compensated by establishing a compensated polar, with the equilibrium being established by deflection α of the elevons; conversely, the errors are further reflected on the slope of the curve $\alpha = f(i)$ of longitudinal flight.

Figure 11 shows the variation in the efficiency factors of the elevons $\frac{\partial Cm}{\partial \alpha}$ and $\frac{\partial C_L}{\partial \alpha}$, as a function of altitude. The values of these coefficients, obtained from measurements made with the floor method and with the image model, show satisfactory agreement. /10

In addition, this particular experimental series has demonstrated that, over a large range of angles of attack (zero incidence at 11°), the efficiency of the elevons remains practically the same over a wide spread of deflection angles of the elevons ($+7.5^\circ \geq \alpha \geq -15^\circ$), with surprisingly linear curves $\Delta Cm =$ $= f(\alpha)$ and $\Delta C_L = f(\alpha)$.

4.2 Aircraft Model with Rear Tail Plane

Experiments on mockups with rear tail group (Plate 12) were made to define whether the separation of flow or, at least, the thickening of the boundary layer of the floor downstream of the wing, might not be such as to completely falsify the ground-effect data.

The experimental series was continued up to extremely low altitudes, even beyond those of the aircraft sitting on the ground.

A comparison of the data, obtained with the floor method and with the image model, shows that the floor method reproduces satisfactorily the lift increment due to the ground effect but, conversely, introduces a considerable distortion of the pitching moment.

Thus, aside from the lift data which agree well at all altitudes (Fig.12), it will be found that the floor method underestimates the increment in Cm_0 and the rearward shift of the aerodynamic center (Fig.13) due to the ground effect.

Conversely, the increase in maximum fineness ratio, resulting from the ground effect (Fig.12) is slightly exaggerated in the floor method, in opposition to what had been observed in tests with tailless aircraft (see Fig.9).

The compensated polars, constructed in accordance with the measurements performed either in the presence of a floor or with an image mockup, agree fairly well. Nevertheless, the curves of longitudinal flight diverge slightly ($\Delta\beta$ resulting from the compensation of the parasite ΔCm, mentioned above).

Since it is possible that, in an aircraft with tail plane, hyperlift flaps can be used, experiments were made on the same model with deflected flaps.

To prevent premature wing-tip stall, the flaps are limited to 74% of the wing span. This precaution was found to be insufficient, so that it became necessary to combine the deflection of the flaps with that of a swivelable tip of the leading edge (deflection η).

The results of comparative tests, using the image method and the floor method, lead to the same conclusions as those obtained from experiments with flaps in neutral position, namely,

satisfactory agreement of the unit lift curves at all altitudes (including altitudes lower than those with extended landing gear);

less rearward shift of the a.c. by the floor method and weaker Cm_0; /11

greater fineness-ratio increase by the floor method, due to the ground effect.

Beyond any concern with respect to the validity of the floor method, experiments on models with deflected flaps have been performed with the image method, so as to demonstrate the true importance of the increase in compensated lift at ground level, produced by hyperlift flaps (see Fig.14).

This particular diagram specifically shows the considerable increase in deflection angle of the tail group, required by the longitudinal balancing at ground level and high angle of attack.

In addition, at low lift values, the $\Delta\beta$ due to the ground effect has a tendency to reverse because of the increment in Cm_0 produced near the ground by the camber effect resulting from the deflected flaps.

The lift values in balanced flight ($Cm = 0$) are similar (Fig.15) to those obtained with undeflected flaps. A study of these graphs shows that the hyperlift balance, although positive, is much less favorable than had been hoped for.

Thus, for an angle of attack of 12°, which closely corresponds to the maximum obtainable incidence at the relative altitude of $H/\ell = 0.3$ (with the rear of the fuselage touching ground at 12.6°), the balanced lift outside of the ground effect is 0.64 with neutral flaps and 0.73 with flaps deflected by 25°, i.e., a lift gain of the order of 14%.

At this same angle of attack, but for an altitude of $H/\ell = 0.3$, the values of the balanced C_L, with neutral or deflected flaps, are 0.8 and 0.87 respectively, i.e., a lift increment, due to the flaps, of 8.8%.

Nevertheless, it seems that the balanced lift in a skimming flight at maximum incidence of 12°, because of the combined effects of ground and flaps, is more than 36% greater than that obtained for the ground effect with neutral flaps.

It is of interest to compare this lift increment with that obtained on a tailless aircraft model.

For this latter, the lowest altitude that can be achieved in flight corresponds more or less to $H/\ell = 0.18$, with a maximum incidence close to 12°, as for the aircraft model with tail unit. Under these conditions, it will be found that the lift in balanced flight is by 27% greater than that obtained outside of the ground effect.

5. Comparison of the Results of Flight Tests and Wind-Tunnel Tests /12

The available data on this particular subject are very few, at least for modern aircraft. So far as tests performed in the Cannes wind tunnel with the floor method are concerned, only comparisons of the rather fragmentary results for tailless aircraft of 60° sweepback are in existence.

These data concern mainly the longitudinal flight. The measurements yielded values on the increase in angle of deflection of the elevons, as a function of the balanced coefficient of lift C_L, at various altitudes (Fig.16).

The lower half of the graph shows the development of the criterion $\frac{\partial \alpha_{elevon}}{\partial C_L}$ as a function of the relative altitude.

It is found that, in the case in question, the wind-tunnel tests faithfully reproduce the ground effect.

6. Aircraft Models with Jet Flaps; Aircraft Lifted by Jets or by Ground-Effect Platforms /13

Models of this type obviously are not suitable for tests with the mirror-image method since, on the one hand, it is difficult to design two absolutely identical jet flaps and since, on the other hand, even if symmetry would be retained from the materiel viewpoint, it seems rather improbable that symmetry of flow about the two models could be obtained in a stable form (interference of the jets).

The use of a wake-separating panel or else the mixed method of half-floor and compensating mockup may be in question; however, in any case, the usefulness of these procedures remains to be proved. Under present conditions, the resultant data do not give sufficient guarantees for establishing a detailed evaluation of the methods.

Recently, tests made in England (Farnborough wind tunnel of 11.5 × 8.5 feet, RAE) yielded interesting results as to the extent of distortions introduced into the measurements of the ground effect by the floor method.

Experiments repeated with "moving belt" or with fixed floors (immobilized conveyor belt) have been made with several typical mockups, equipped with various pressure slots: jet-flap aircraft, V.T.O.L. (vertical takeoff/landing aircraft) with lift tubes, etc.

The rather sketchy results ever published on this subject are plotted in Figs.16 and 17. A study of these results reveals that the data obtained in the presence of a fixed floor fairly well reproduce the general course of the development of lift and longitudinal stability produced by the ground effect; however, the numerical values of the results were found to be quite erroneous, as soon as the aerodynamic influence due to the ground effect increased.

7. Conclusions /14

The critical evaluation of the mode of representation of the ground in a wind tunnel, specifically a comparison of results obtained by the mirror-image wing and by the fixed "floor", indicates that this latter procedure leads to greatly erroneous results if aircraft models equipped with wings of weak sweepback are involved.

Conversely, such a study also makes it possible to obtain relatively close values of the ground effect, using aircraft models equipped with wings of strong sweepback. Specifically, the increments in lift and in aerodynamic fineness ratio, resulting from the ground effect, are quite correctly obtained by the floor method, even when the wing has hyperlift and when the mockup is provided with a rear tail unit.

So far as the longitudinal stability of this type of mockup is concerned, the floor method slightly underestimates the rearward shift of the aerodynamic center as well as the Cm_0, but the reaction of these systematic errors on the aerodynamic characteristics in a balanced aircraft model are hardly noticeable. Only the curve of the longitudinal flight is somewhat affected, without however showing an extensive change in its overall slope.

Experiments with representation of pressure slots or of lift-producing jets have not been made in any comparative and systematic manner. However, some measurements performed by the RAE seem to indicate that the application of the method of a fixed floor to this type of aircraft models leads to a considerable distortion of the results as soon as the aerodynamic effect of the ground becomes significant, i.e., exactly at the moment when the measurements become of greater interest. Nevertheless, the general slope of the curves, indicating the influence of the ground effect, is maintained, thus permitting a qualitative estimate during the stage of preliminary investigations.

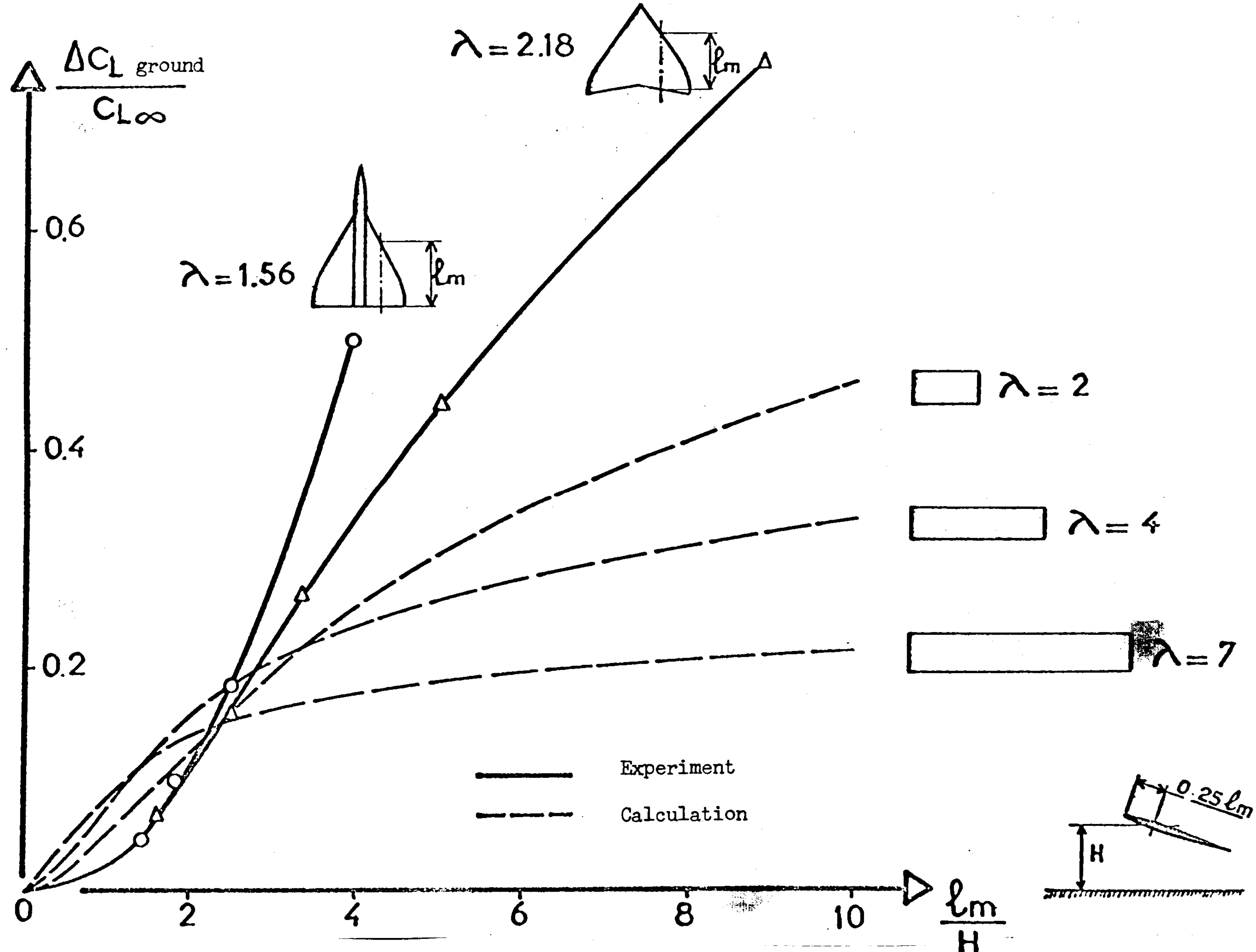

Fig.1 Increase in Lift due to the Ground Effect

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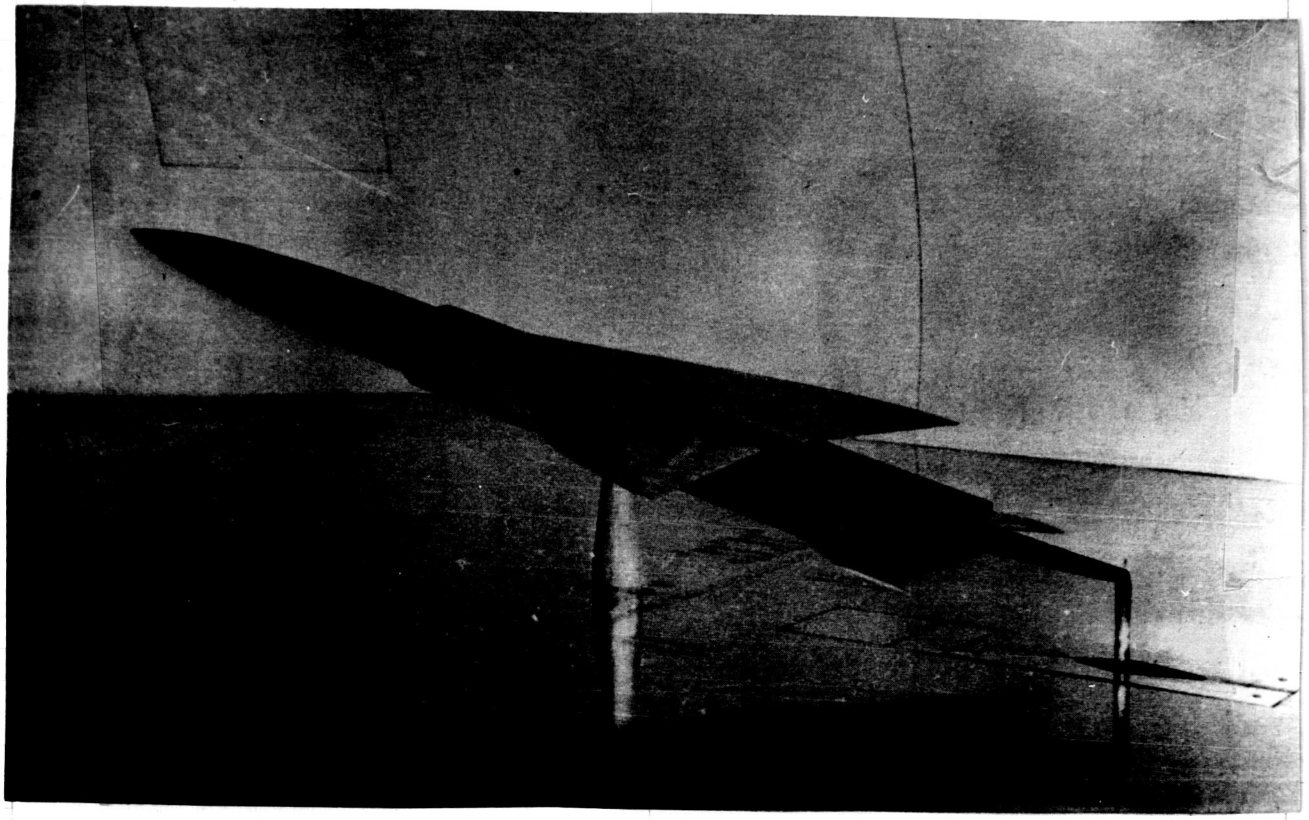
Fig.2 Wind Tunnel S_1 atCannes; Representation of the Ground by the Mirror-Image Method

/17



(The above photograph has been reversed; in reality the model is suspended in the inverse position, as indicated below)

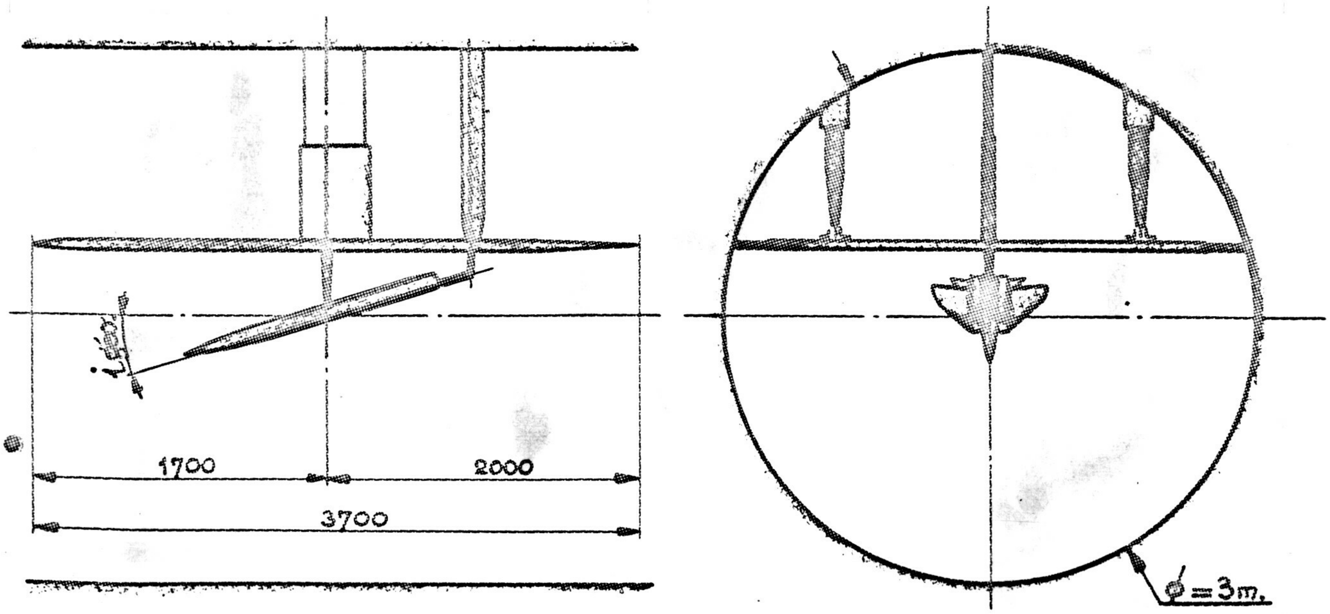
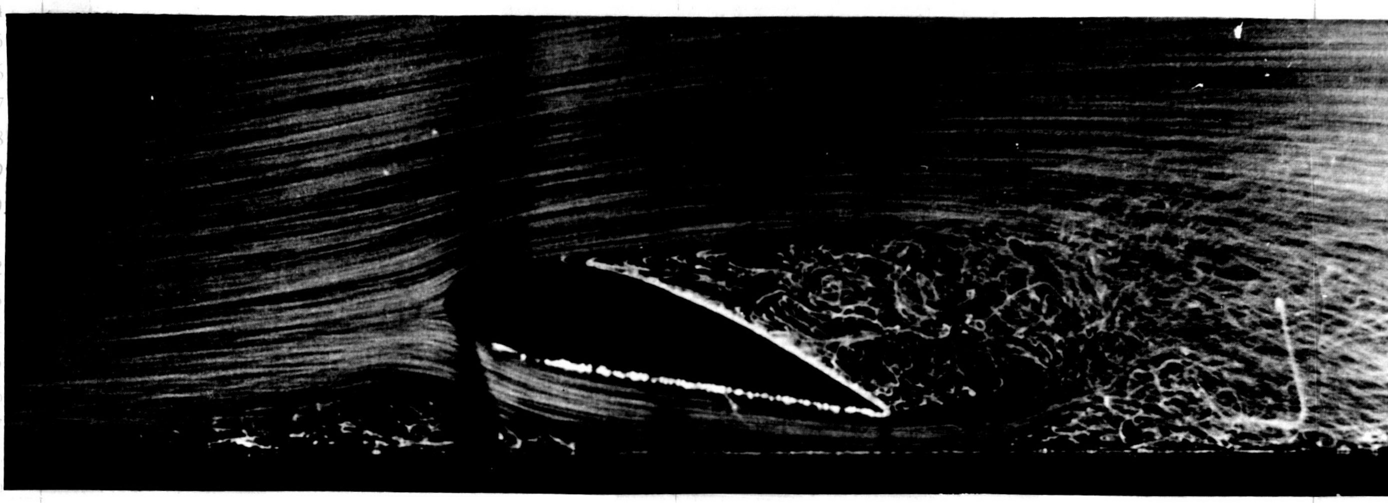


Fig.3 Wind Tunnel S_1 at Cannes; Representation of the Ground by a Floor

Profile G.L.21 $i = 10^{\circ}$ $H/l = 0.125$



Floor Method

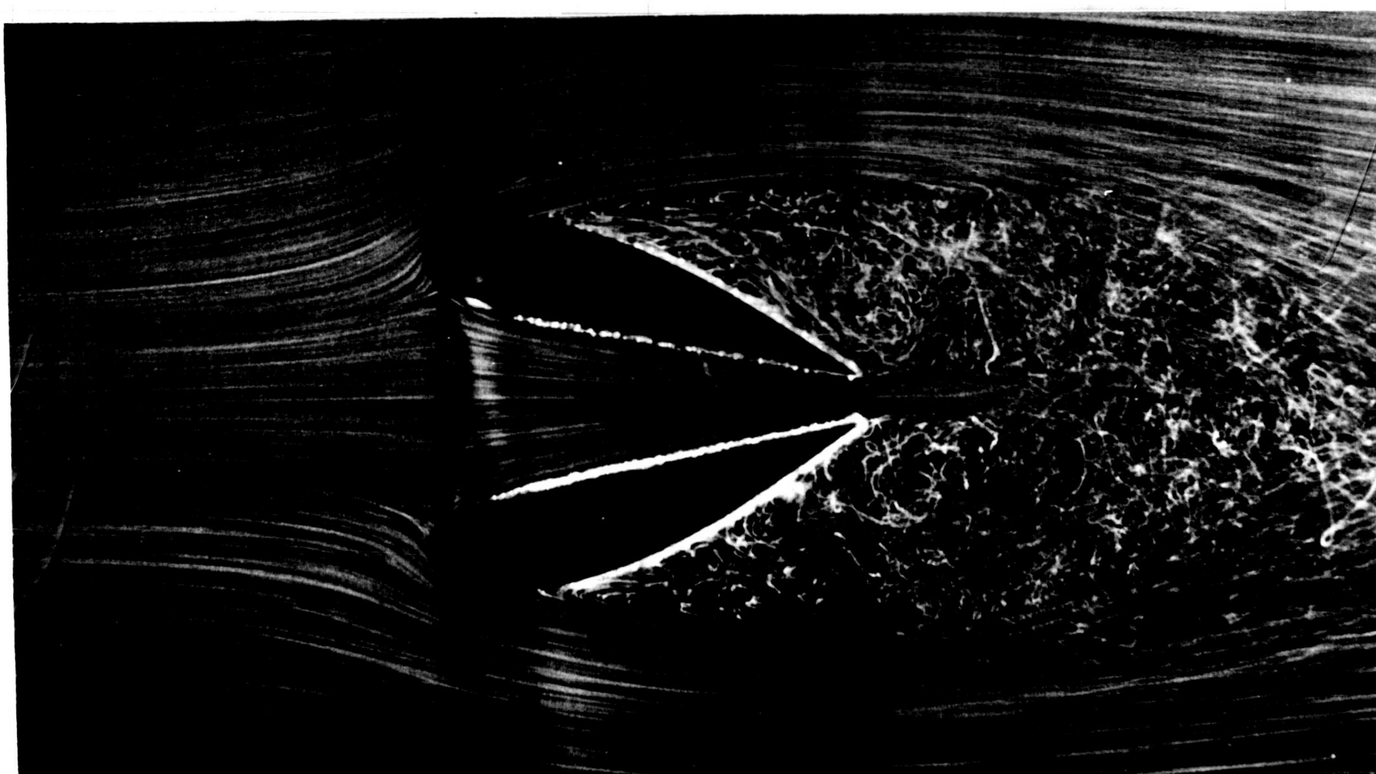


Fig.4 Visualization of the Ground Effect

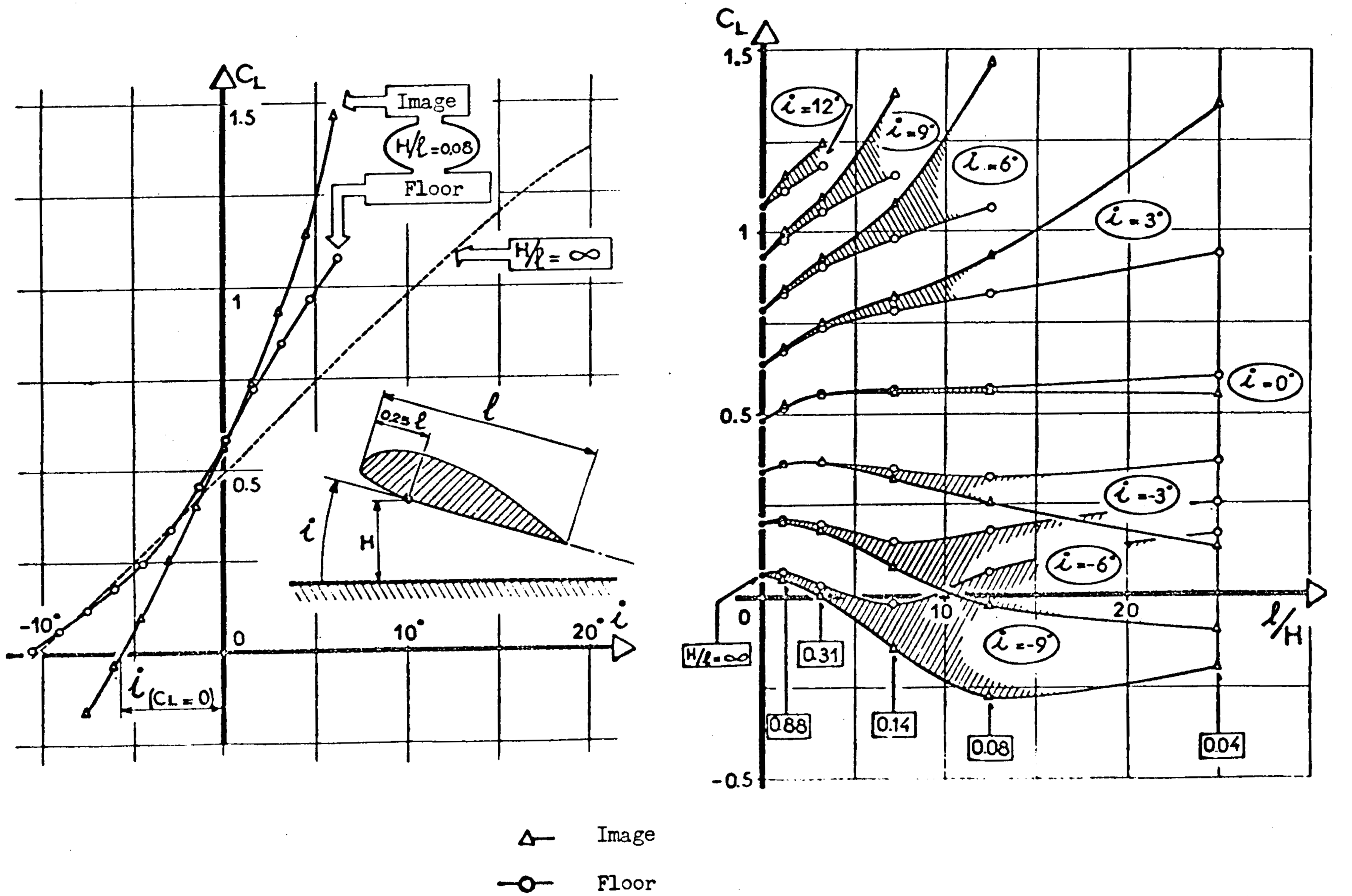


Fig.5 Rectangular Wing λ = 2

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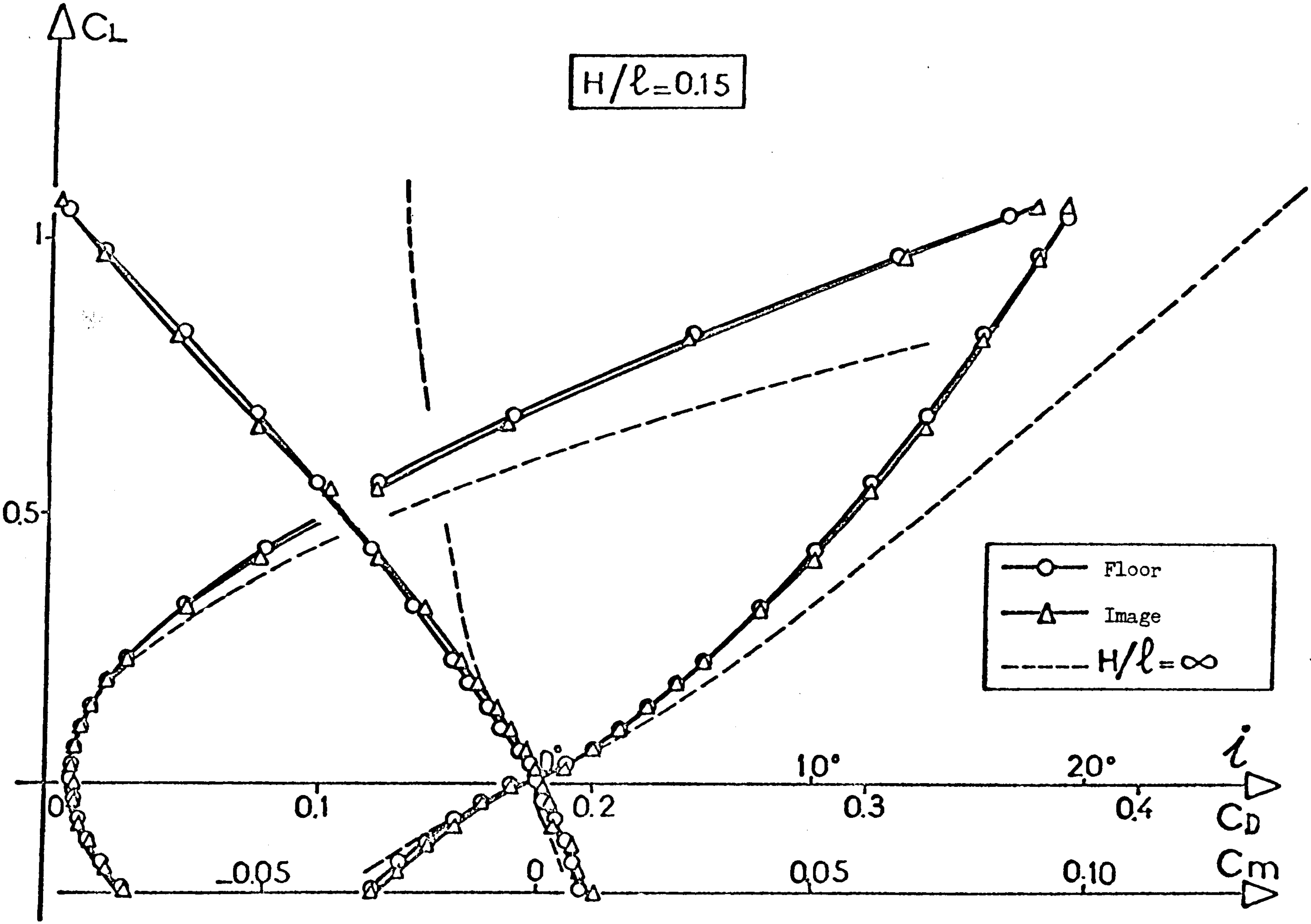

Fig.6 Delta Wing, 75°

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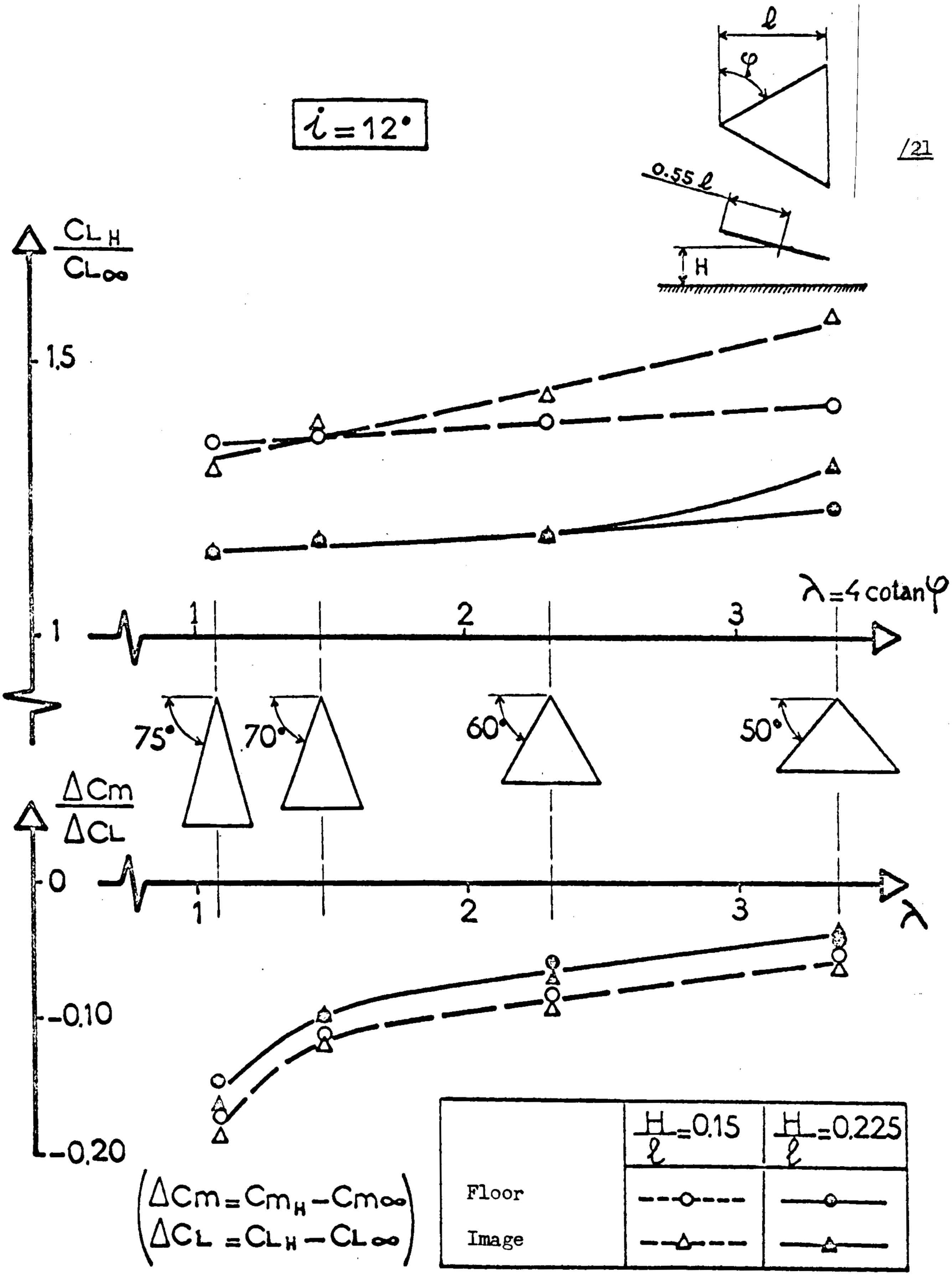

Fig.7 Flat "Delta" Wings

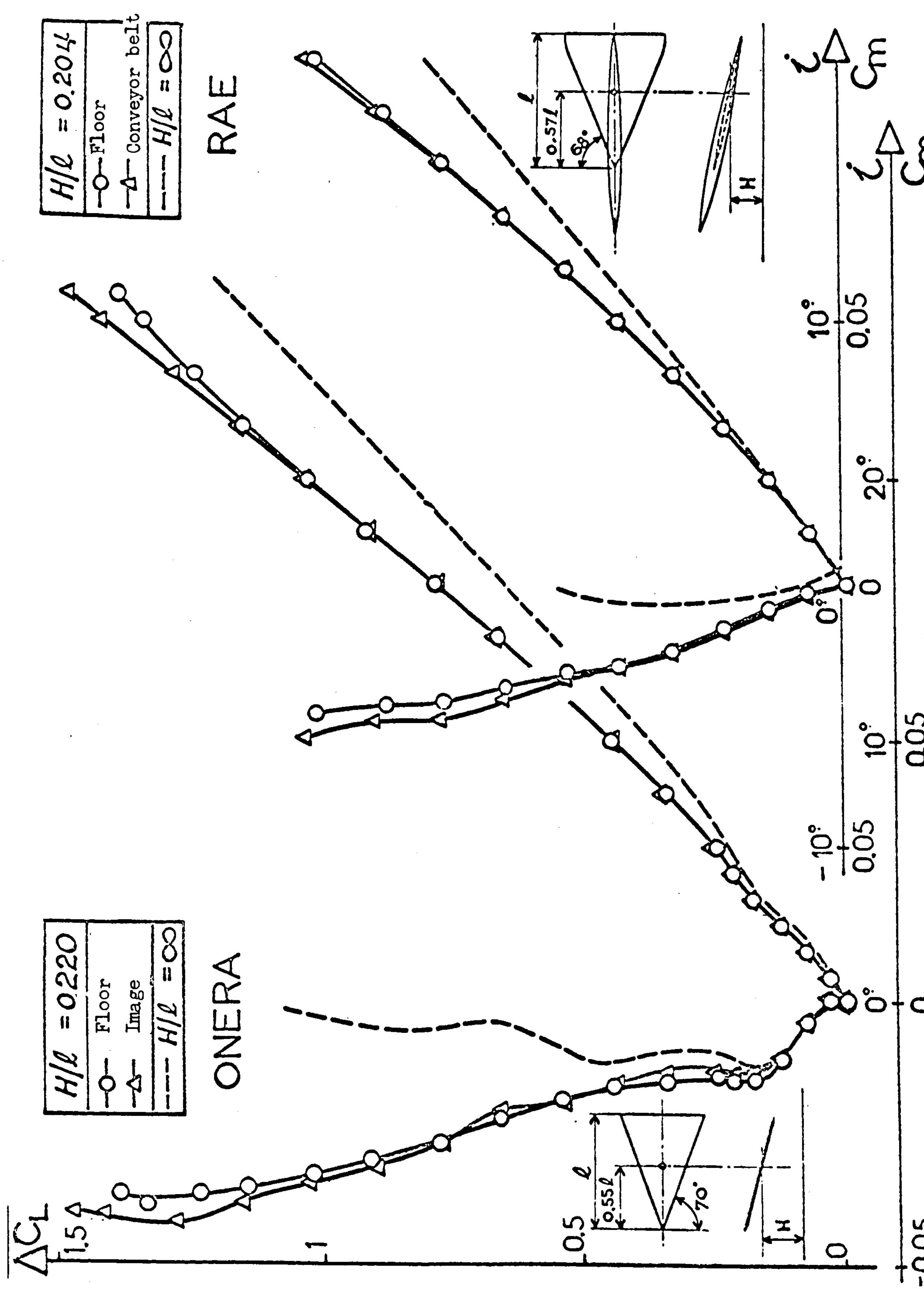

Fig.8 Comparison

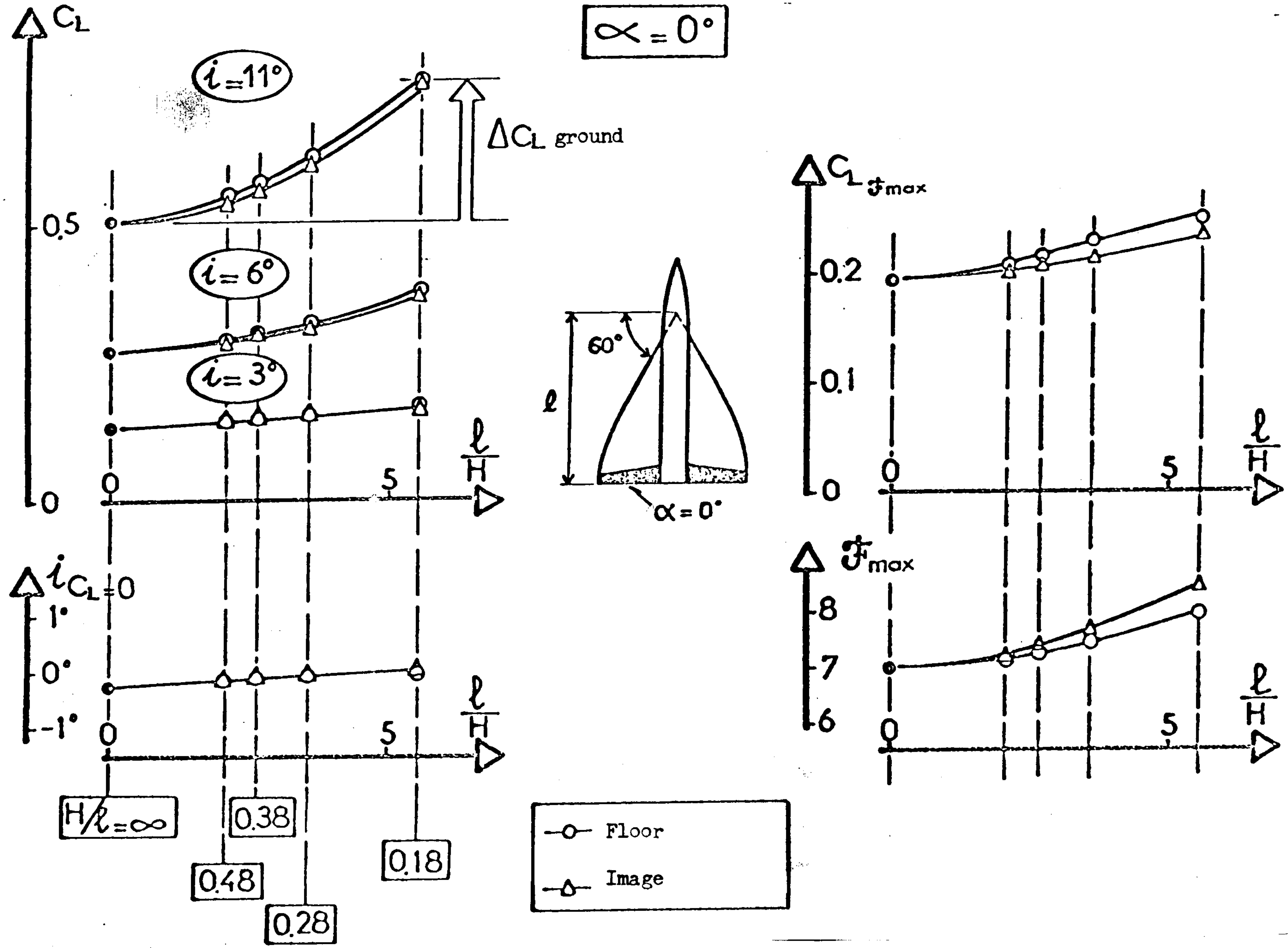

Fig.9 Tailless-Aircraft Model

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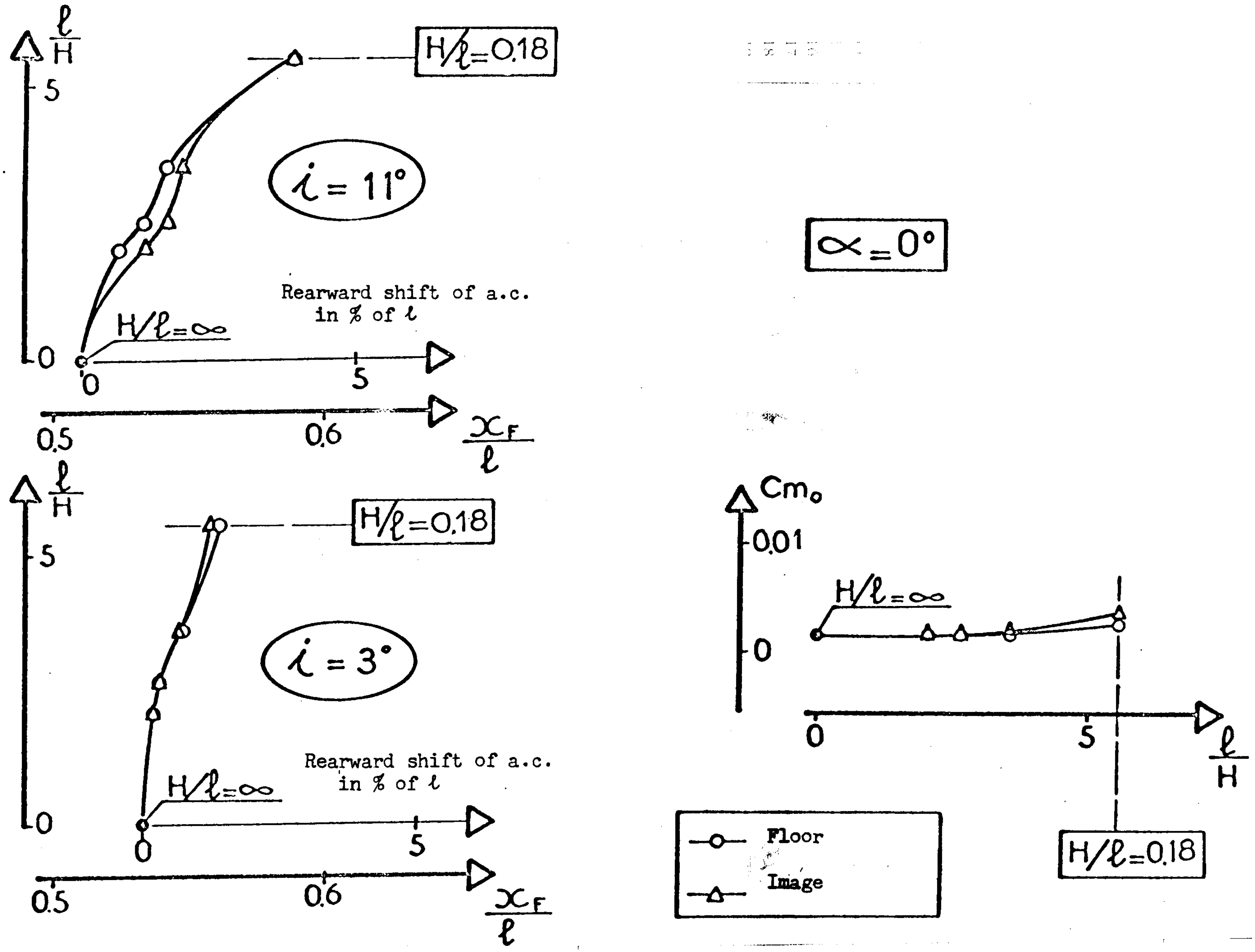

Fig.10 Tailless-Aircraft Model

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Efficiency criteria of the elevons

$(7.5° \geq \alpha \geq -15°)$

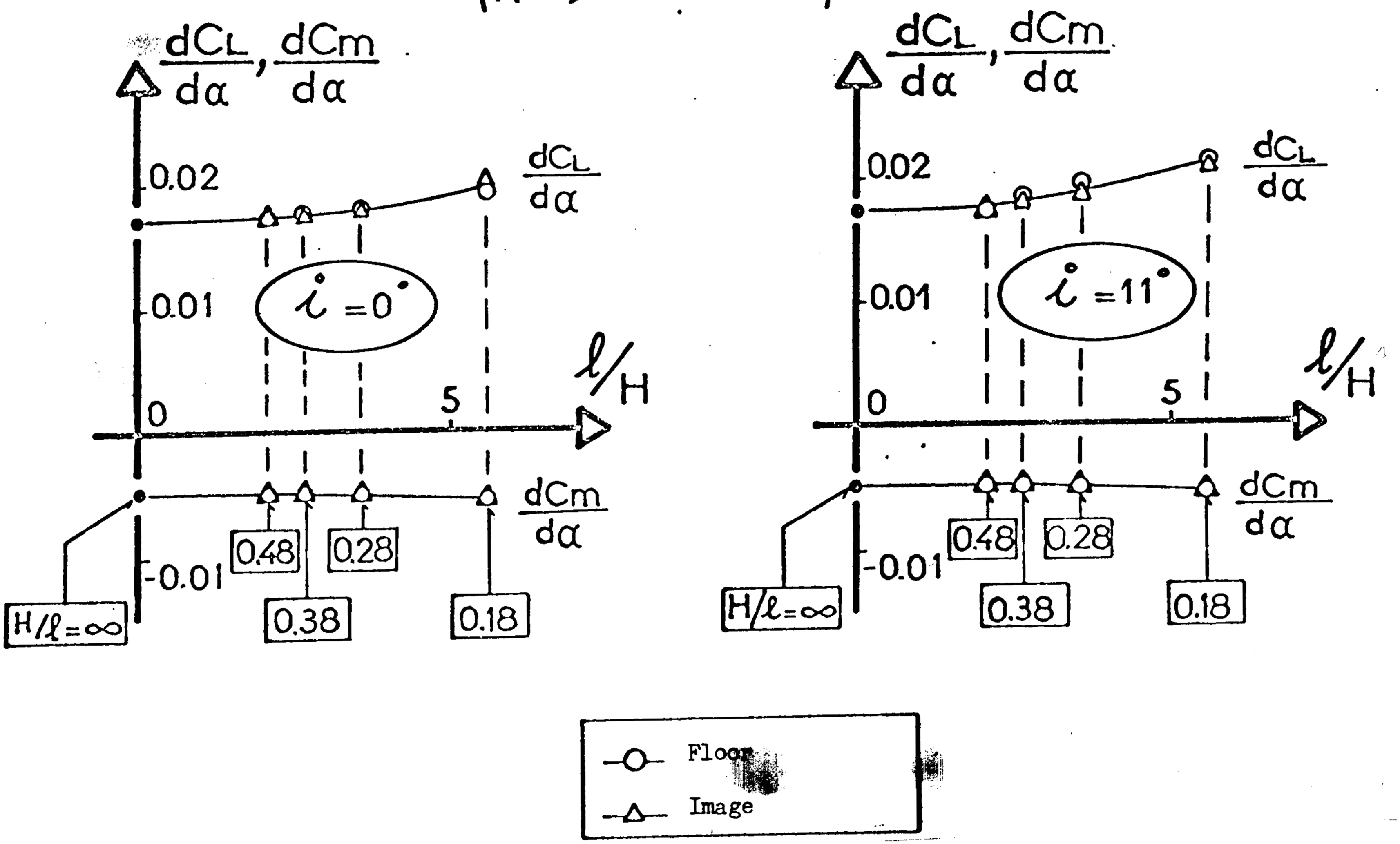

Fig.11 Tailless Aircraft Model; Centering 0.5 l

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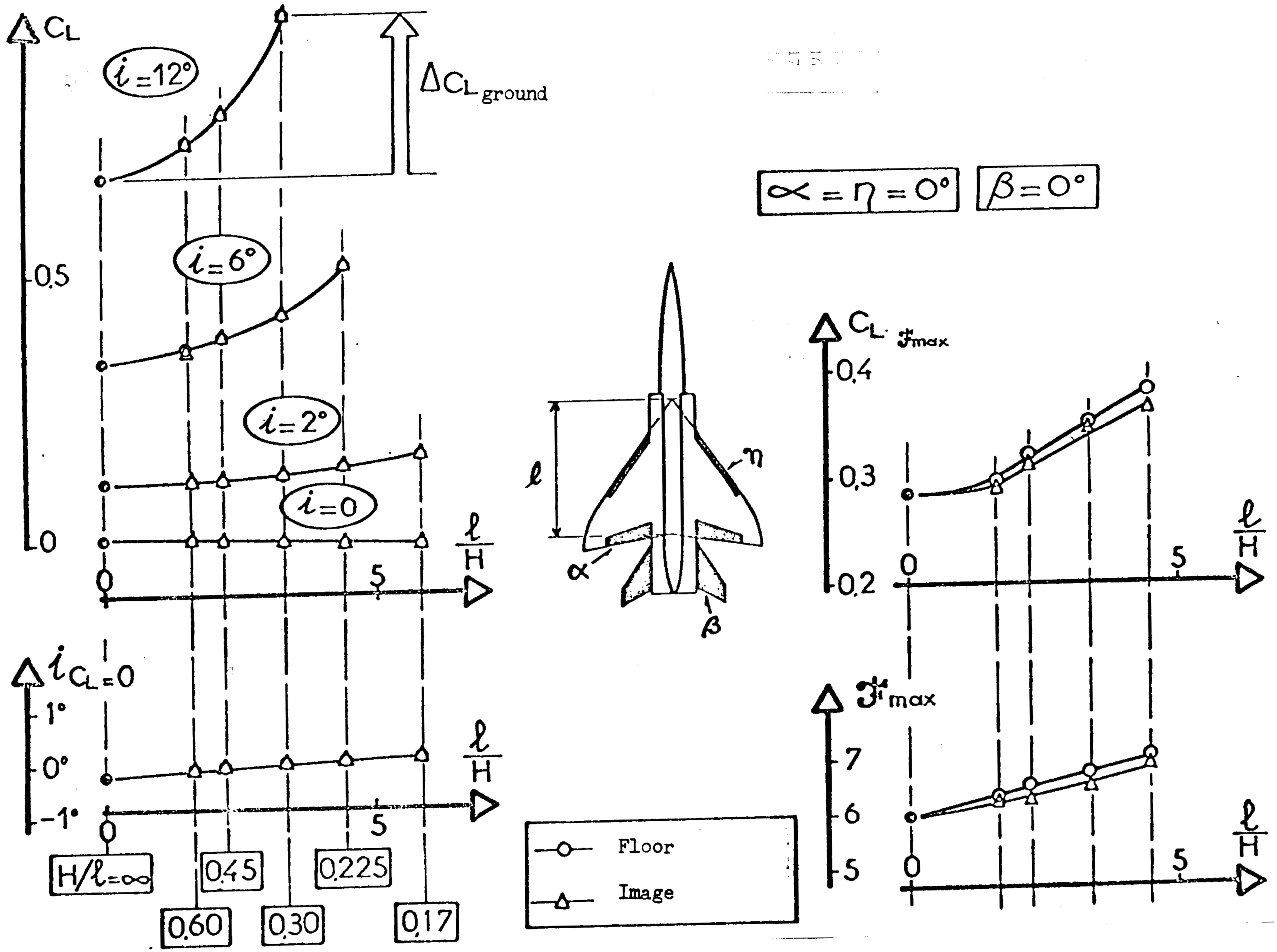

Fig.12 Aircraft Model with Tail Plane

/26

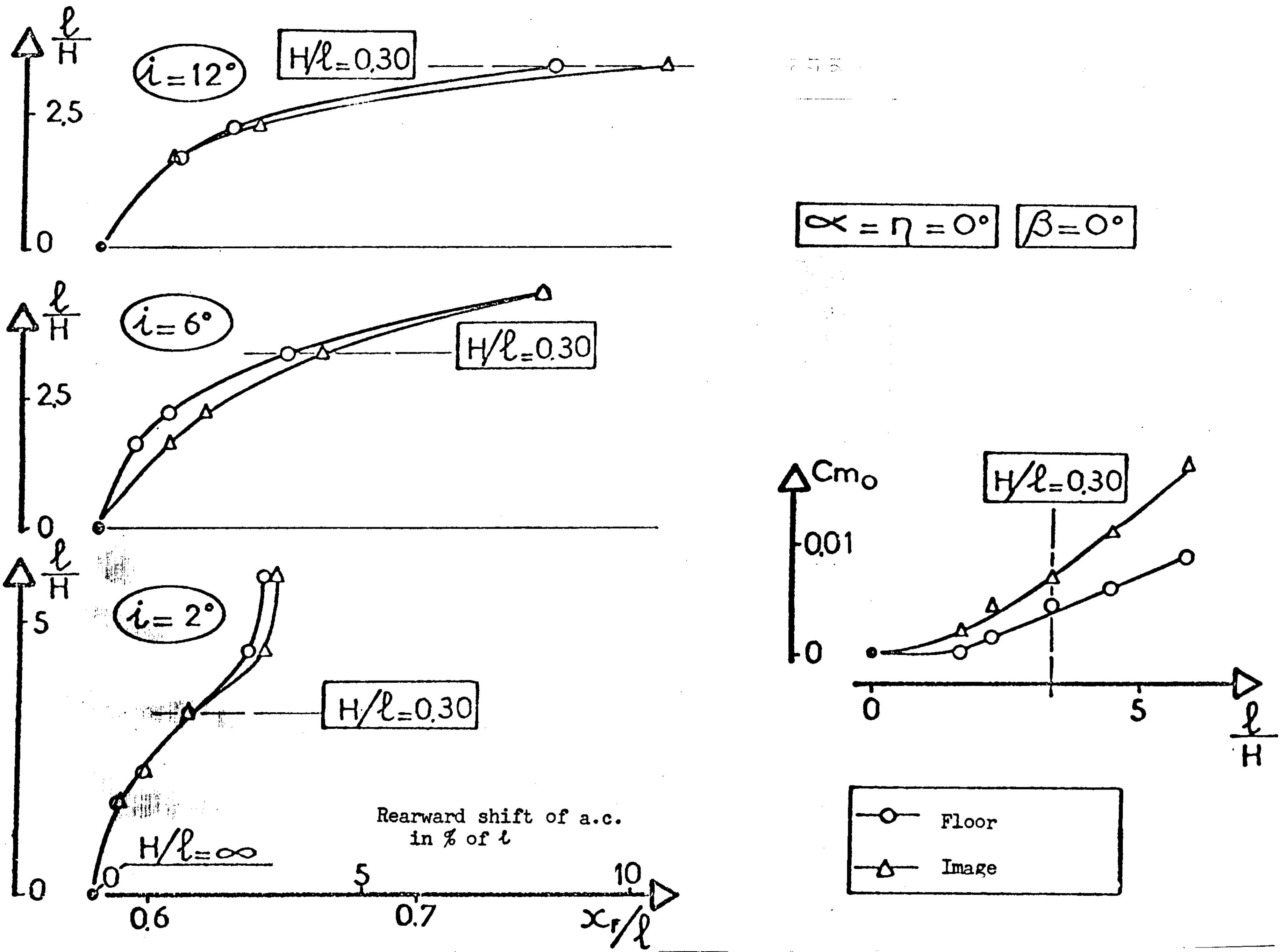

Fig.13 Aircraft Model with Tail Plane

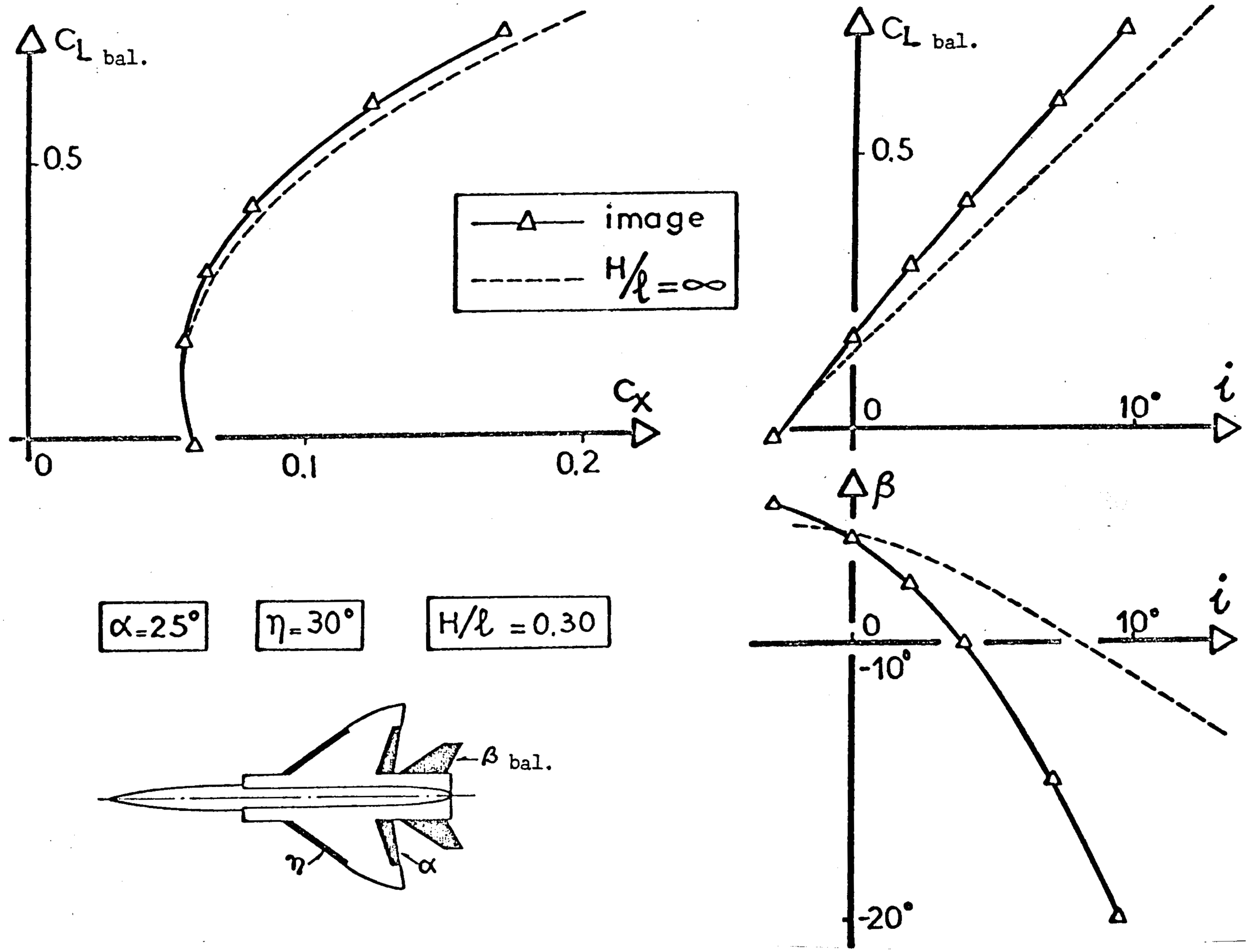

Fig.14 Aircraft Model with Tail Plane

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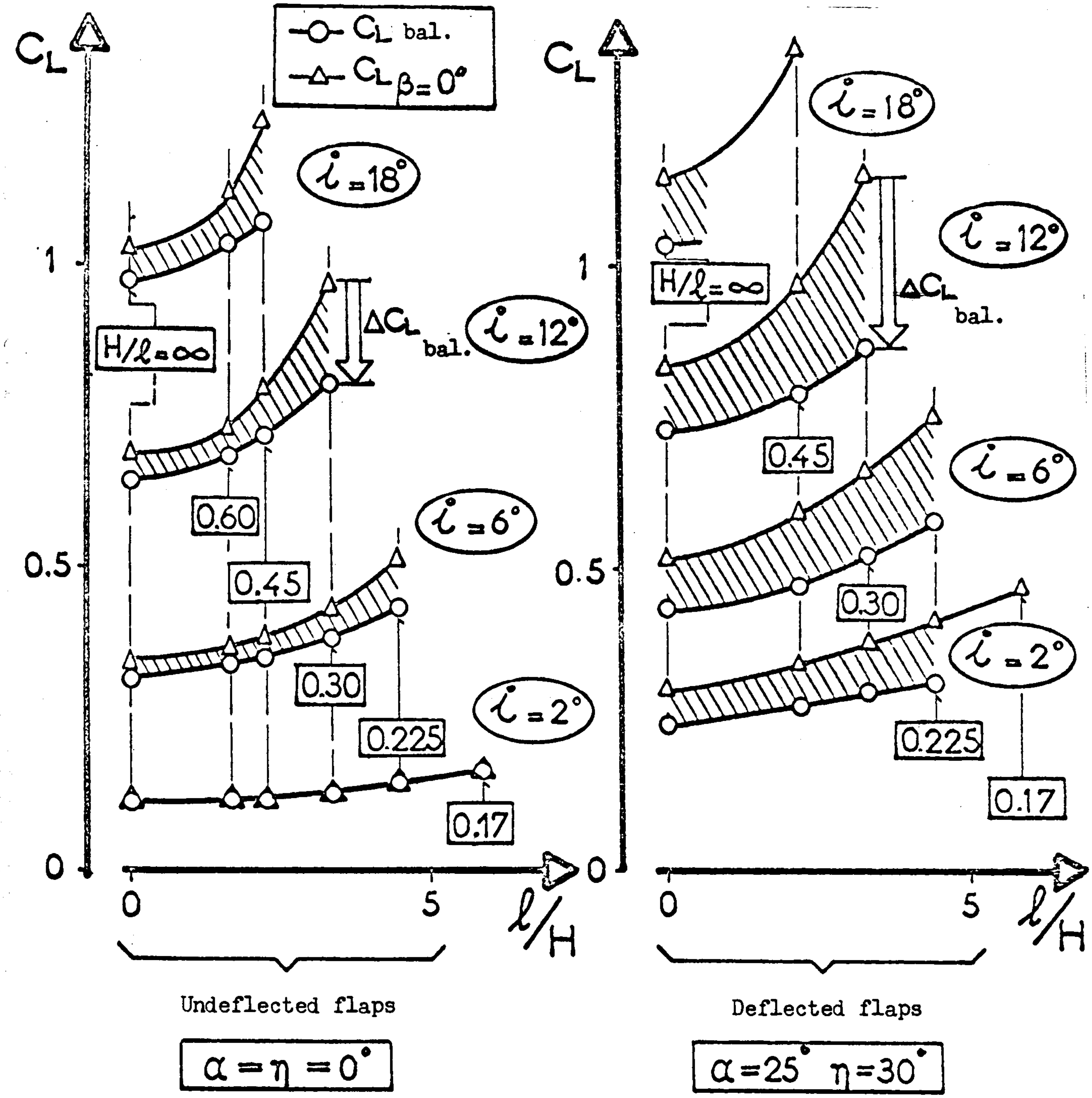

Fig.15 Aircraft Model with Tail Plane; Centering 0.5 ℓ

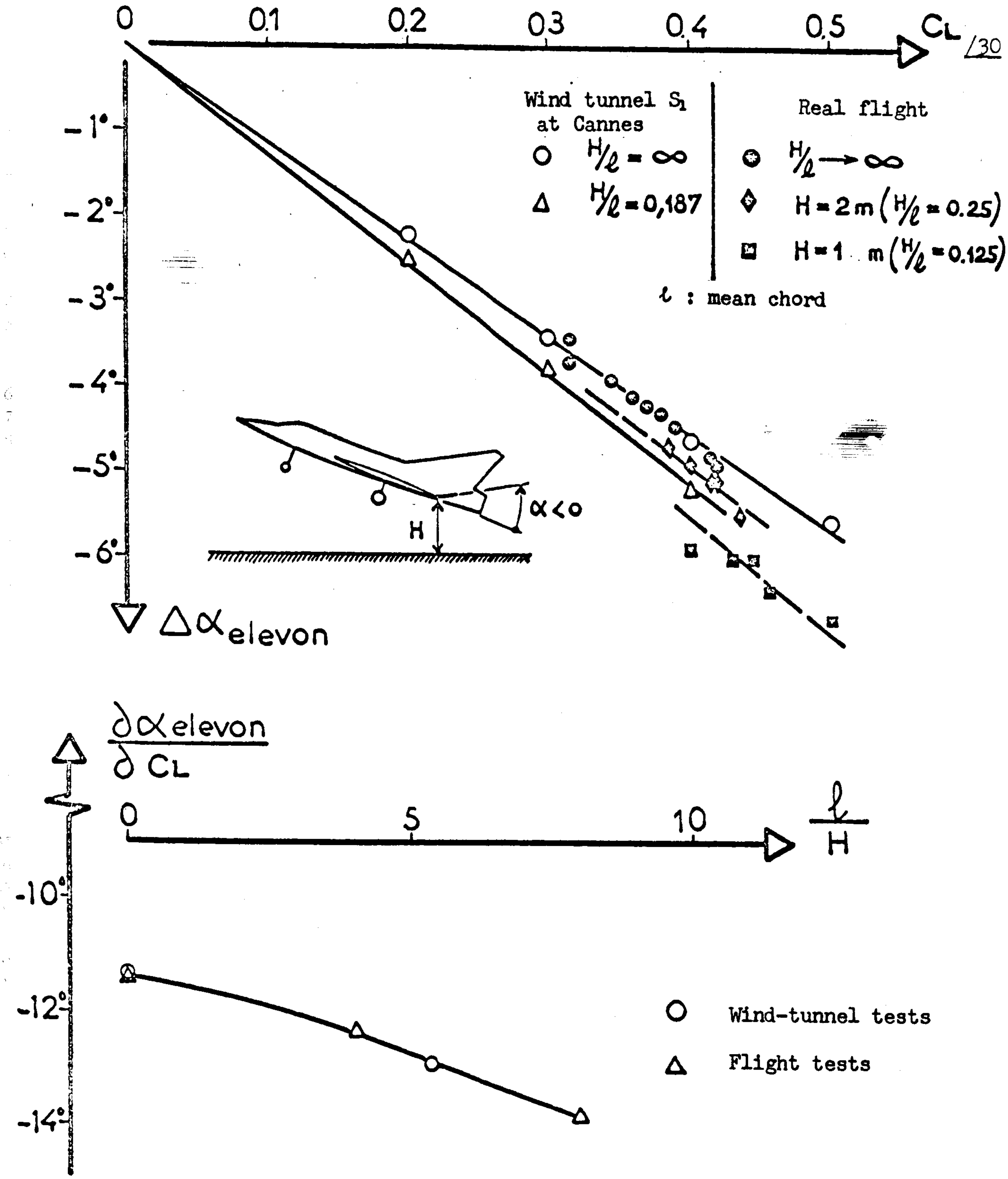

Fig.16 Delta Aircraft $\varphi = 60^{\circ}$; Comparison of Wind-Tunnel Test Results with Flight Tests

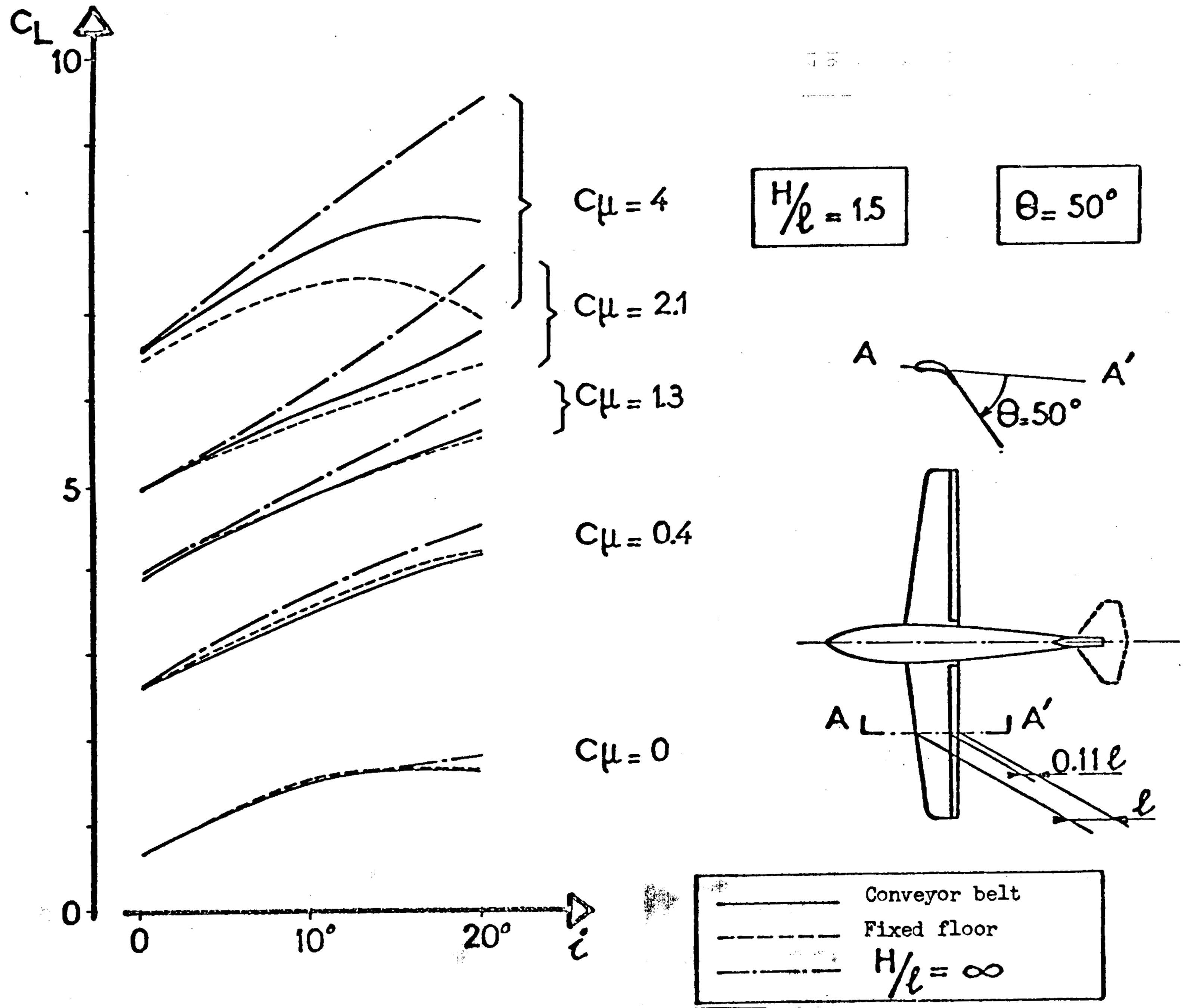

Fig.17 Jet-Flap Aircraft

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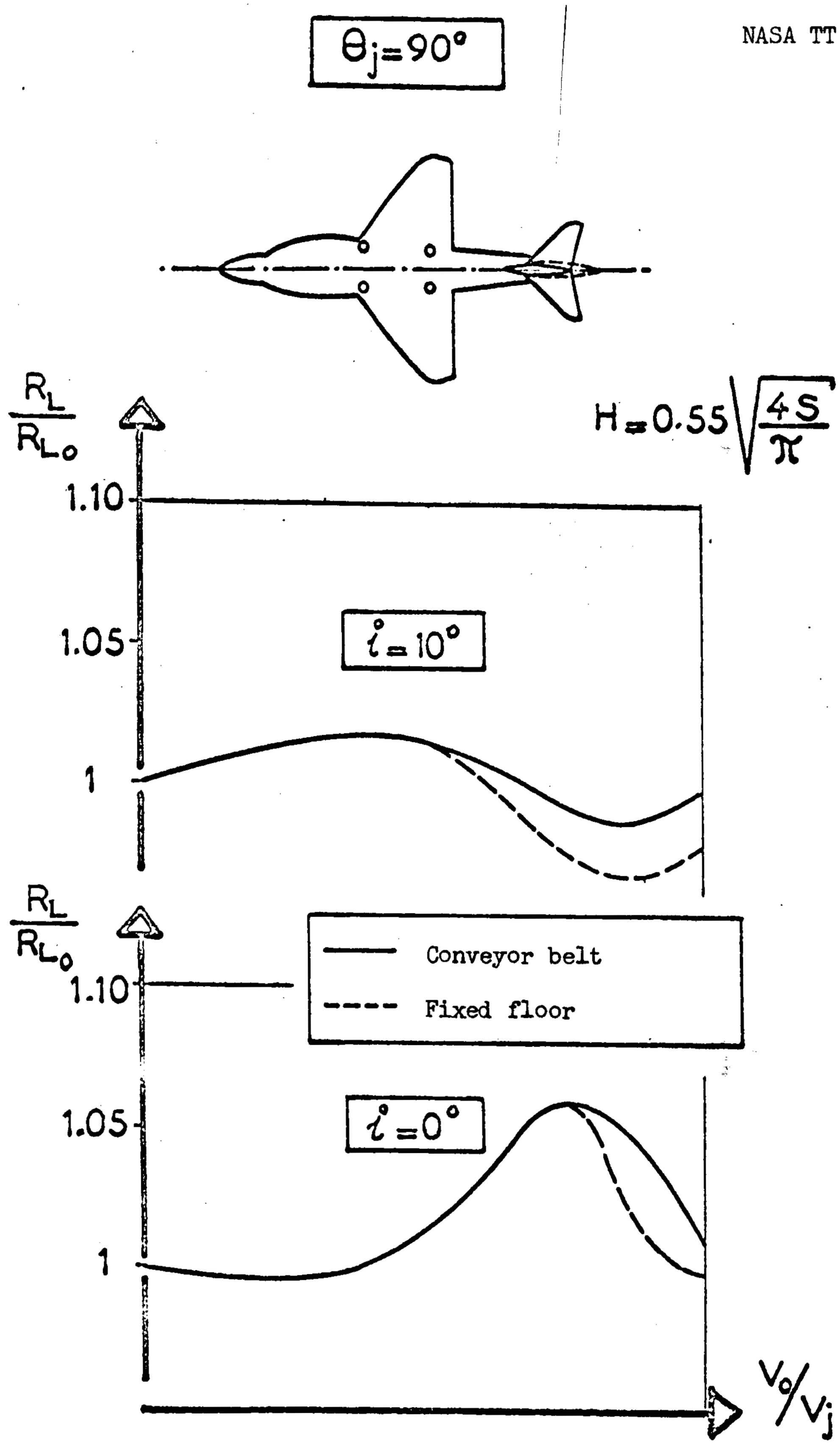

Fig.18 V.T.O.L. Aircraft with Lift Tubes